Tropospheric Emission Spectrometer (TES)
Ozone Data Description

1. Intent of This Document

1a) This document is intended for users who wish to compare satellite derived observations with climate model output in the context of the CMIP5/IPCC historical experiments. Users are not expected to be experts in satellite derived Earth system observational data. This document summarizes essential information needed for comparing this dataset to climate model output. References are provided at the end of this document to additional information.

This NASA dataset is provided as part of an experimental activity to increase the usability of NASA satellite observational data for the modeling and model analysis communities. This is not a standard NASA satellite instrument product, but does represent an effort on behalf of data experts to identify a product that is appropriate for routine model evaluation. The data may have been reprocessed, reformatted, or created solely for comparisons with climate model output. Community feedback to improve and validate the dataset for modeling usage is appreciated. Email comments to HQ-CLIMATE-OBS@mail.nasa.gov .

Dataset File Name (as it appears on the ESG):

tro3_Amon_obs_Obs-TES_obs_r1i1p1_200507-200912.nc

1b) Technical point of contact for this dataset:

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2. Data Field Description

CF variable name, units:	tro3, 1e-9.
Spatial resolution:	The longitude and latitude resolution is 2.5 degree by 2 degree.
Temporal resolution and extent:	Monthly averaged between July 2005 and December 2009.
Coverage:	Global.

Note: The vertical pressure levels include the subset of the CMIP5 mandatory levels (700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, 250 hPa, 150 hPa, 100 hPa, 70 hPa, 50 hPa, 30 hPa, 20 hPa, and 10 hPa). The other three CMIP5 mandatory levels (1000 hPa, 925 hPa, and 825 hPa) are outside of the TES measurement vertical range and are filled with the filler value 1.0e+20.

3. Data Origin

TES ozone concentration is not an *in situ* measurement but a remotely sensed one by measuring the infrared-light energy emitted by gases and particles in Earth's atmosphere. An ozone vertical profile is retrieved using the TES observed infrared-light energy and a nonlinear forward model of the radiative transfer from the atmosphere through the instrument. The retrieval process involves a constrained nonlinear least squares fitting procedure to minimize the difference between the observations and the forward model outcomes (Bowman et al. 2006). The vertical resolution of TES ozone retrievals is about 5-10 km for nadir observations and for cloud-free scenes, with sensitivity to both the lower and upper troposphere (Worden et al. 2004). While TES can have two observational modes (nadir and limb views), this data product contains only nadir-view observations. The retrieved ozone values are binned in a regular grid with a 2 degree by 4 degree box and is monthly averaged, resulting in this data product.

4. Validation

TES ozone profiles are validated by the comparisons with ozone sonde and lidar measurements. The comparisons show that TES generally sees higher ozone in the lower and middle troposphere than the sondes and lidar (Nassar et al. 2007; Richards et al. 2007). These validation studies show that TES ozone estimates are typically biased high in the upper troposphere by approximately 10%. TES total column ozone is also compared with measurements from other satellite instruments such as Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS). The comparisons show similar global distributions, but TES measures 3-7% more ozone (Osterman et al. 2007).

5. Consideration for Model-Observation Comparisons

Because this data product is observational data, there are several aspects that distinguish this product from model outputs. The user of this data product should be aware of them in order to make judicious model-observation comparisons.

5.1 Time Sampling Bias

Because TES is on board the Aura satellite with a sun-synchronous polar orbit, it samples at the two fixed local solar times at each location (e.g. 1:43 AM and 1:43 PM at the equator) and does not resolve the diurnal cycle (TES website). TES observations at a given latitude on either the ascending (north-going) or descending (south-going) portions of the orbit have approximately (to within several minutes) the *same* local solar time throughout the mission, as indicated in Figure 1 (TES level 3). In contrast, typical model monthly averaged outputs contain the averaged values over a time series of data with a fixed time interval (e.g. every 6 hours). For many constituents in the upper atmosphere, this difference is not likely a problem although for regions influenced by deep convection and its modulation of the diurnal cycle (e.g. tropical land masses), this time sampling bias should be considered.

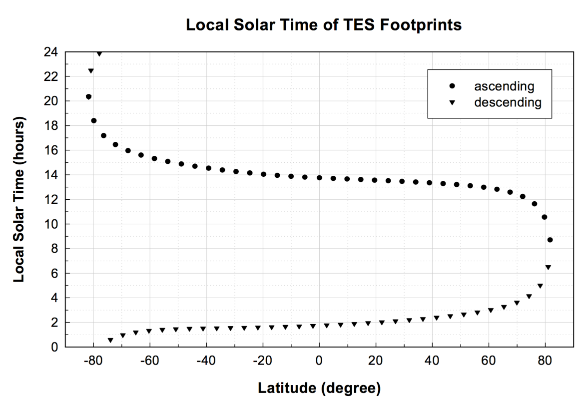

Figure 1: Local solar time when TES observes a given latitude on the Aura sun-synchronous polar orbit.

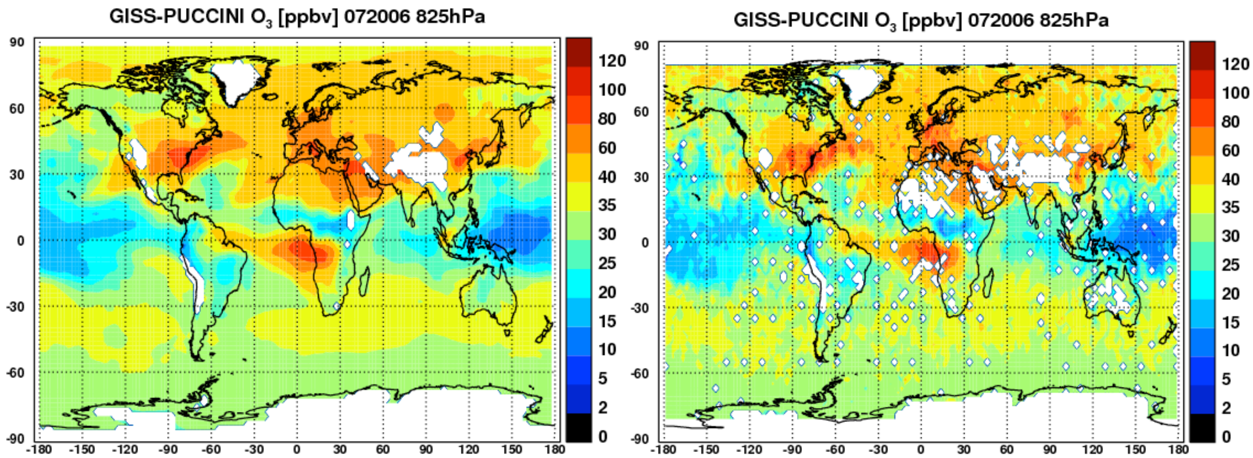

Figure 2. The influence of spatio-temporal sampling in the GISS-PUCCINI model output. The figure shows the comparison of model monthly mean (left) and the mean of model sampled across TES profiles, averaged to the model original resolution (right).

As an example, Figure 2 illustrates the influence of spatio-temporal sampling using the GISS-PUCCINI model output (Shindell D. T *et al.* 2006). The figure shows the comparison of model monthly mean and the mean of model sampled across TES profiles (which is averaged to the model original resolution). The figure shows that despite the coarse diurnal sampling by TES, the monthly mean calculated from the sampled profiles is able to capture the synoptic scale variability of ozone in the July 2006 when TES performed 42344 total number of independent observations. The influence of sampling is currently being investigated for a longer time period.

5.2 Inhomogeneous Sampling

Because the monthly averaged value in this TES data product is an average over observational data available in a given lat-lon box, the number of samples used for averaging varies with the geo-location of the box. Due to the geometry of the Aura sun-synchronous polar orbit, there are no observations above latitude 80° and there are more observations near the boundary (70°-80°) than the rest of the area. Figure 3 illustrates the typical number of samples included in each grid box for this TES monthly averaged data product. A routine operating procedure for the TES global survey is to make continual sets of observations in a 1-day-on and 1-day-off cycle (Beer. R. 2001). Hence a monthly average only comprehends half of a month worth of observations.

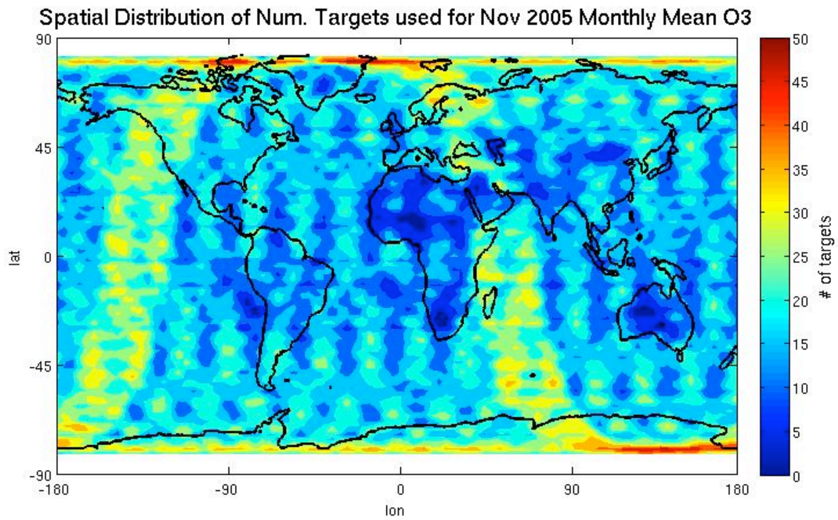

Figure 3: Distribution of the typical number of samples used for the monthly averaged TES data.

5.3 Anisotropic and Inhomogeneous Resolution

While a typical model output has a fixed horizontal resolution in latitude and longitude degrees and a fixed vertical resolution as prescribed, TES nadir observations has varying resolutions due to its viewing geometry and radiometric sensitivities. The TES horizontal resolution is 0.5 km along track and 5 km across the orbit track, and thus is not fixed in latitude and longitude degrees. The TES vertical resolution is approximately 5-10 km and depends on pressure level and geolocation (Worden et al. 2004).

The sample data used in the monthly averaging are the collection of observations whose footprint centers (boresights) are located in a given grid box. This means that the averaged value for a given grid box contains a fraction of observations from the neighboring boxes due to the mismatch between the gridded box resolution and the TES native observation resolution.

5.4 Averaging Kernel Application

The sensitivity of the TES retrieved ozone vertical profile to the "true" ozone profile is ultimately limited by spectral resolution, signal-to-noise ratio, and information content in the spectral signatures. Mathematically, the instrument sensitivity can be represented by the averaging kernel matrix, of which the rows define the relative contribution of each element of the true vertical profile to the estimate at a particular pressure level. With a perfect sensitivity as in the case of model outputs by definition, the averaging kernel matrix is the identity matrix, making the retrieved profile equal to the true profile. In reality, the averaging kernel matrix is "broadened" from the identity matrix due to the limited sensitivity. The full width at half maximum of the rows of the averaging kernels is a measure of the vertical resolution of the retrieved profile.

Figure 4 shows the TES ozone averaging kernel matrix. Each line represents the row of the matrix. The figure shows that the TES retrieved ozone profile has a complex relationship with the true profile, and the retrieved ozone vertical resolution (approximately the width of the main

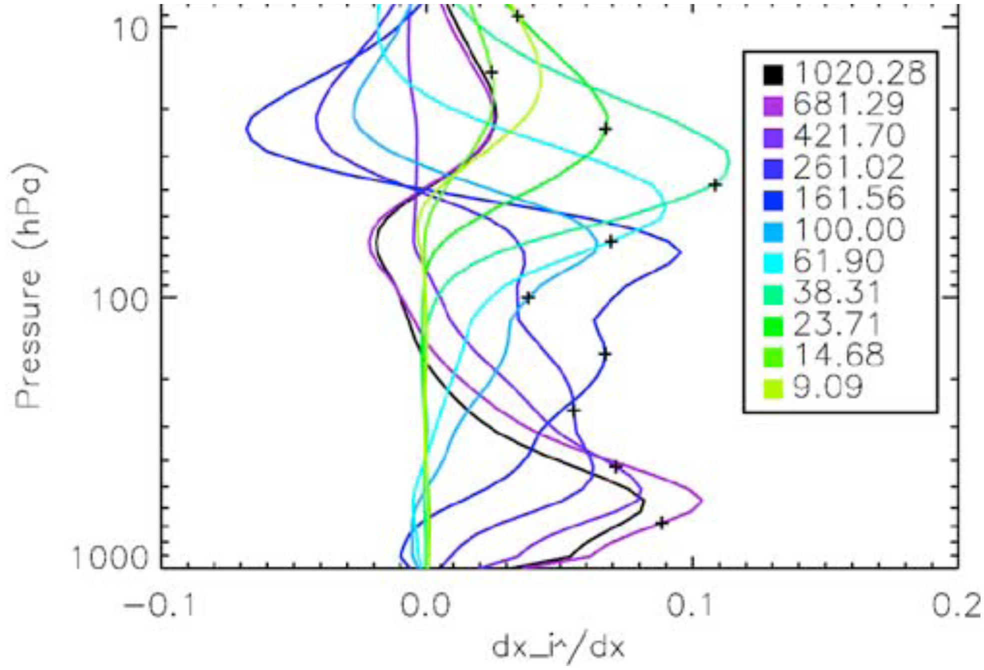

Figure 4. TES ozone averaging kernel matrix. The rows of this matrix are plotted for different pressure levels of the retrieved ozone profile. The black cross-hairs are the pressure levels corresponding to each averaging kernel.

curve) is much larger than the CMIP5 vertical resolution. For example, the retrieved ozone value at pressure level of 681.29 (light purple line in Fig. 3) contains the contribution from pressure levels of 900 hPa to 300 hPa using the full width of the half maximum (FWHM) rule. The FWHM contains six CMIP5 vertical levels: 825 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa. The mismatch of the vertical resolution and sensitivity between TES and CMIP5 models can be taken into account by applying the averaging kernel matrix to the model output, creating TES-like synthetic measurements out of the model outputs, and compare the synthetic measurements with the TES observations. More details on the application of the TES observation operator can be found in Kulawik 2009 and Bowman *et al.* 2009.

6. Instrument Overview

The Tropospheric Emission Spectrometer (TES) is a high-resolution infrared imaging Fourier transform spectrometer spectrometer covering the spectral range 650–3050 cm^{-1} (3.3–15.4 μm) at a spectral resolution of 0.1 cm^{-1} (nadir viewing) or 0.025 cm^{-1} (limb viewing) (Beer et al 2001; TES website). TES is optimally designed to determine the chemical state of the Earth's lower atmosphere (the *troposphere*) (Beer 2006). In particular, TES produces vertical profiles 0–32 km of important pollutant and greenhouse gases such as carbon monoxide, ozone, methane, and water vapor on a global scale every other day (Beer 2006).

TES is one of four instruments on the [NASA's EOS Aura satellite](), launched on July 15th 2004. Aura is in a near-polar 705 km altitude sun-synchronous orbit. As Earth rotates underneath it, the Aura orbit stays fixed relative to the sun and gives daily global coverage at a fixed local time for the half of an orbit and another fixed local time for the other half at a given location with ~13 orbits per day. Aura is part of NASA's A-train group of Earth observing satellites. These satellites fly in formation with the different satellites making measurements within a short time of each other as shown in Figure 5.

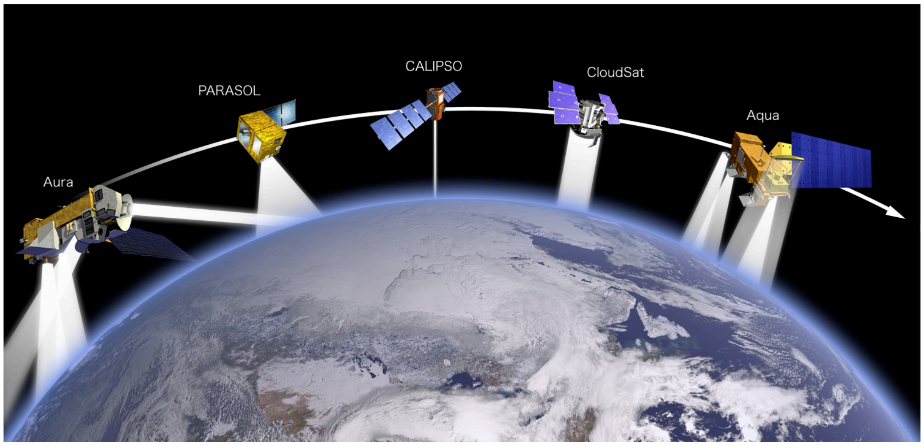

Figure 5: NASA's A-train group of Earth observing satellites.

The orbit repeats its ground track every 16 days (233 orbits). Standard Products are produced from *Global Surveys*. Global Surveys consist of a sequence of observations that takes about 82 seconds and is repeated continuously for 16 orbits in just over one day (Beer, 2006). Figure 6 shows the coverage during the 16-orbit global survey. At present, the TES record is nearly 6 years long and provides a global measure of the annual cycle and monthly variability of the vertical profiles 0-32 km of trace gases in the atmosphere.

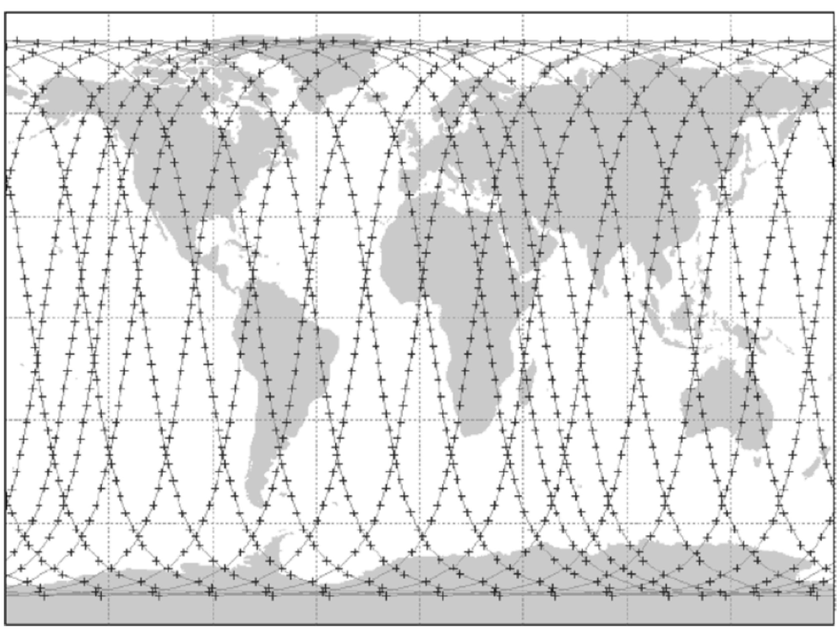

Figure 6: Coverage during a typical 16-orbit Global Survey (crosses). There are eight such surveys undertaken during the 16-day repeat period of the orbit.

7. References

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8. Revision History

Rev 0 - 7/18/11 -